A Theoretical Analysis of Why Black Powder Model Rocket Motors Fail or "*Why Motors Sometimes Go BOOM*"

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INTRODUCTION

The catastrophic failure of a model rocket motor (or a "cato", as it is commonly known) often generates a great deal of discussion. The reasons for the failure of the motor are blamed on a variety of causes. Despite the development work done by Flannigan and Shector on the causes of catos in D12 motors, very little theoretical work has been done to explain why model rocket motors fail as they do. This paper will present the reasons why black powder model rocket motors fail.

SUMMARY

Over the past years, numerous studies have demonstrated that black powder model rocket motors will fail if exposed to temperature extremes. What has not been presented in the past is the isolation of the causes of these failures.

Using basic structural analytical techniques, it can be shown that the standard model rocket motor has a basic design problem when exposed to high temperatures. Typically, the grain expands more than the case would at a given temperature. When the grain cools, the case does not necessarily return to its previous position, but instead may suffer from creep, leaving a gap between the grain and case. This gap then becomes a failure point, allowing the grain surface area to be larger than designed. This causes casing overpressurization, which results in either a case rupture or "spitting the grain".

Large black powder motors with cores (such as the FSI Loadlifter series) have additional stresses that make them even more likely to cato.

These theoretical predictions closely match the experimental data generated to date.

From a design standpoint, improvement would be likely if the motor case was less susceptible to creep. Going to a thicker case wall is also an option, but will only work up to a point.

Until black powder motor case improvements are made, rocketeers would be wise to keep their rocket motors from being exposed to temperature extremes.

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BACKGROUND

Motor Design

A black powder model rocket motor consists primarily of the following components:

Casing	A convolute wound paper tube
Nozzle	A modified deLaval design that channels the flow of the hot gases and particles produced during combustion
Propellant	A pressed black powder charge
Delay Train	A slow burning, smoke producing mixture that allows the rocket to coast
Ejection Charge	A small gas producing charge that is intended to activate the recovery system

Figure 1 presents a cutaway diagram of a typical black powder motor.

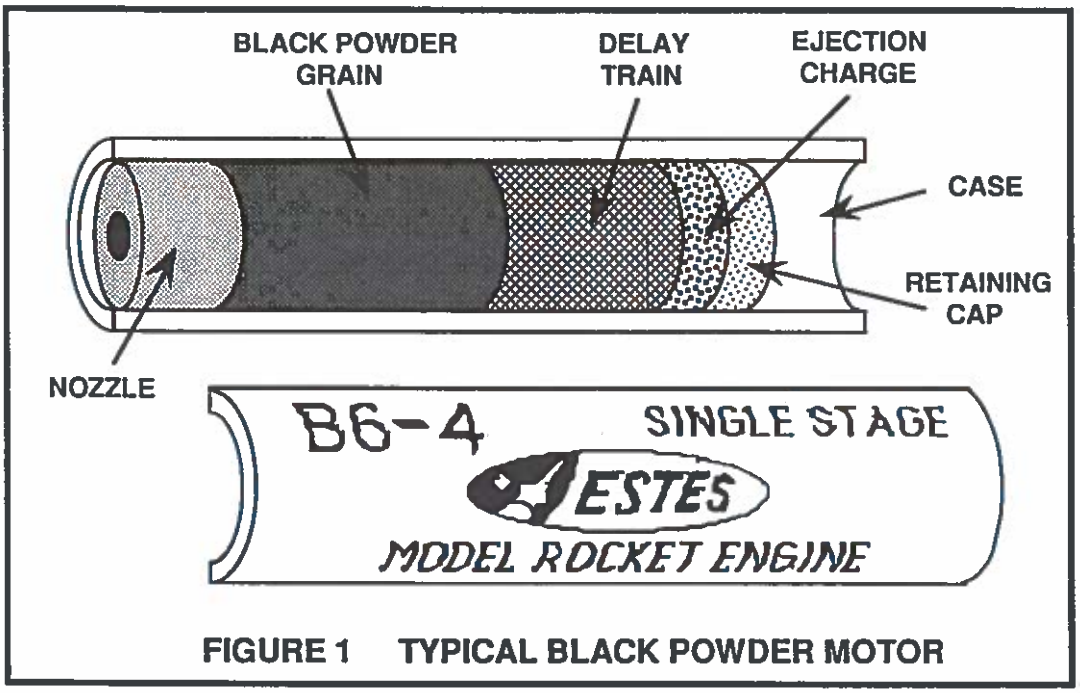

FIGURE 1 TYPICAL BLACK POWDER MOTOR

Motor Manufacture

Typical model rocket motors are made by compressing the black powder charge, nozzle, and delay train into the casing. Usually, hydraulic or pneumatic rams are used, exerting considerable pressure. The casing expands slightly during the ramming process. The resulting tension at case/grain interface holds the grain in place. The case, as a result, has an induced loading condition.

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Figure 2 illustrates the basic equilibrium state of the completed model rocket motor.

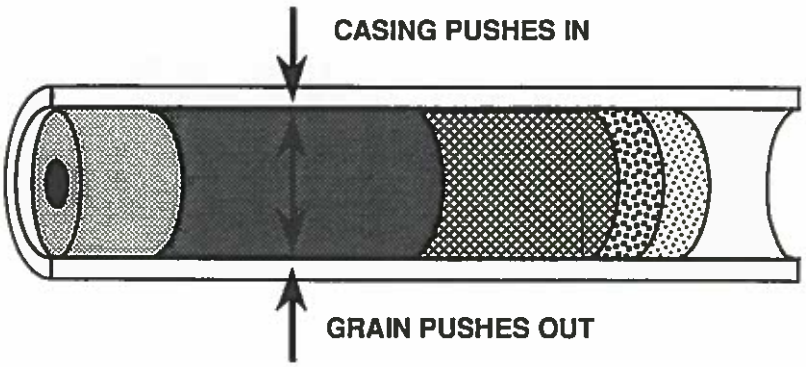

FIGURE 2 EQUILIBRIUM STATE OF A BLACK POWDER MOTOR

Observed Failure Mechanisms

In the most extensive study performed to date (432 D12 motors), Fred Shector discovered that motors exposed to temperature extremes would incur separations of the case/grain interface.

Figure 3 illustrates this condition.

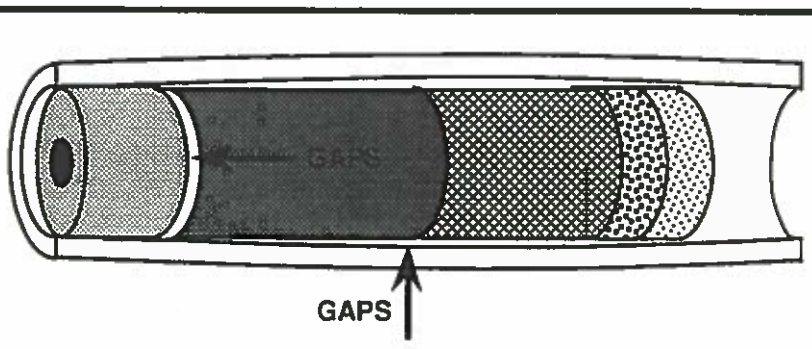

FIGURE 3 SEPARATIONS AFTER TEMPERATURE CYCLING

Shector noted that this condition could induce failures by increasing the burning surface area of the propellant. This in turn would produce more combustion gas and particles, resulting in an overpressurized condition. That, in turn, would lead to a catastrophic failure of the rocket motor.

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Figure 4 illustrates normal motor operation

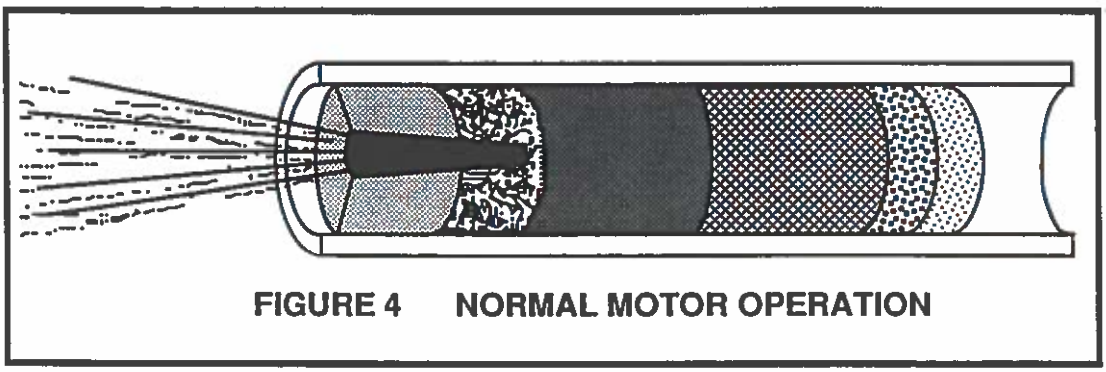

FIGURE 4 NORMAL MOTOR OPERATION

Figure 5 illustrates the burning that occurs when a grain/case separation occurs.

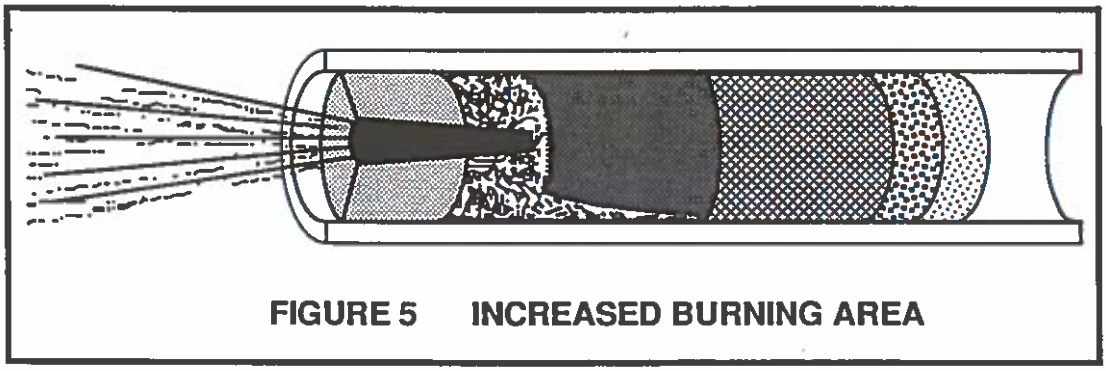

FIGURE 5 INCREASED BURNING AREA

Figure 6 illustrates a catastrophic failure.

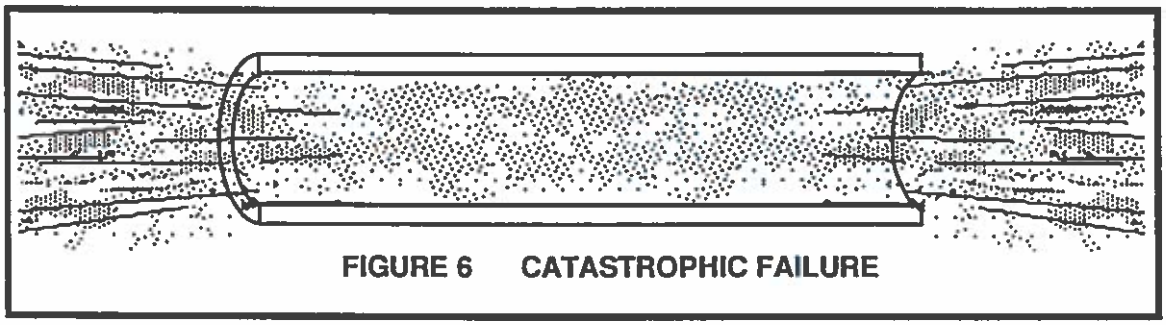

FIGURE 6 CATASTROPHIC FAILURE

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OBJECTIVE

It was the objective of this study to present a sound theoretical basis for the causes of grain/case separations when black powder rocket motors are subjected to temperature extremes.

APPROACH

This paper identified two areas of interest: 1) the effects of thermal excursions on the case and grain, and 2) to examine the structural characteristics of the motor casing.

In order to keep this paper on an understandable level that most rocketeers can understand, I will only present a general argument and generalized results. In order to perform a more detailed analysis of this problem, a finite element analysis and thermal coefficient of expansion measurements should be conducted. However, this would be an expensive and time consuming endeavor, and would yield little useful data except to the motor designer. It is not the scope of this paper to go into that level of detail.

I have chosen to present only basic structural analytical models and rough order of magnitude calculations to explain the failure mode mechanisms in general.

DISCUSSION

Basic Analysis

A basic analysis of the structural characteristics of a rocket motor considers:

a) the source and character of the loads
b) the character of the stress bearing materials
c) the interaction of the stresses

Of primary interest in this case are the loads induced due to thermal cycling and the loads induced at ignition.

For thermal cycling, we know that tension and compression from thermal expansion causes stresses on the grain surface. This may induce cracking of the grain at the case/grain interface. In cored motors, these stresses can cause cracking of the inner core.

At ignition, the case generally expands and the grain compresses. In end burning motors, the axial pressure differential is great . Any area of grain fracture or debonding may be a source of motor failure.

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Thermal Effects

Black powder is a relatively low performance propellant that has been in use since the first model rocket motors were developed. Although the content may vary, Table I presents typical black powder components.

TABLE 1

Black Powder Components

	Typical %
Potassium Nitrate (Saltpeter)	75.0
Sulphur	12.5
Carbon, Amorphous (Charcoal)*	12.5
	100.0

* Gunpowder charcoal, usually made of alder, willow, or hazelwood, is about 95-97% carbon and 3-5% ash. For the purposes of this analysis, it will be assumed to be 100% carbon.

Source: Chemistry of Pyrotechnics

In my research I could not find any evidence that casing or black powder grain coefficient of thermal expansion measurements had ever been made or even considered. However, a search of reference texts revealed that there were established values for most of the major components of black powder model rocket motors. This information is presented as Table 2.

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TABLE 2

MATERIAL COEFFICIENT OF CUBICAL EXPANSION

Material	Mean value * ($\times 10^{-6}$)
Sulphur	223.0
Potassium Nitrate	196.7
Carbon, Amorphous	23.6
Clay, ceramic	24.3
Paper casing	102.3 **
Iron	355.0
Copper	488.8
Lead	839.9
Rubber	4870.0
Parafin	5880.0

* Between 32° deg. and 212° deg. F
** Based on wood, across fiber values
Source: Handbook of Physical Properties

One fact becomes apparent after examining the data in Table 2. That is, two of the major components in black powder have very large coefficients of expansion compared to other materials used.

After examining the expansion coefficients of the black powder materials, it is clear that the sulfur and potassium nitrate mixture have relatively high values in comparison to the carbon. Since black powder is a physical mixture rather than a chemical composition, it is reasonable to assume that expansion coefficient will be largely a function of the sulfur and potassium nitrate, with the effects of the carbon being rather small. Also, since the sulfur and potassium nitrate make up 82.5% of the total mixture, it is reasonable to assume that the actual expansion coefficient is probably in the range of 196.7 - 223.0. For the purposes of this analysis, I have selected a value of 196.7 (the value for potassium nitrate) for the black powder expansion coefficient. Due to the low coefficient of expansion for the carbon, its effect has been considered to negligible.

This is intended to be conservative. I suspect that the actual coefficient may be closer to the value of sulfur. Since the interactions are not well understood, though, I thought it may be more realistic to analyze the expansion of the largest component, potassium nitrate. This may, in actuality, understate the actual calculations of thermal expansion, but will not mask the effects.

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From the equations

(Equation 1) $L = L_o\ (1 + C\ V_E)$

and

(Equation 2) $L_E = \frac{V_E}{3}$

where
L_0 = length of material at 0° C
L = length of material
C = temperature of material (°C)
V_E = coefficient of volumetric expansion
L_E = coefficient of linear expansion

we can calculate what the increase or decrease in diameter of a propellant grain might be at a given temperature.

Table 3 shows the calculated growth of a black powder grain as a function of temperature. Figure 7 depicts it graphically for the Estes D12.

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TABLE 3

TEMPERATURE VS. GRAIN DIAMETER

Motor Type	Temperature °F (°C)	Diameter (inches)	Difference from Ambient (in)
Estes Mini Motor	0 (-17.78)	.2497	- .0006
	32 (0)	.2500	- .0003
	70 (21.11)	.2503	
	100 (37.78)	.2506	+ .0003
	125 (51.67)	.2508	+ .0005
	150 (65.56)	.2511	+ .0008
Standard Estes Motor	0	.4994	- .0013
	32	.5000	- .0007
	70	.5007	
	100	.5012	+ .0005
	125	.5017	+ .0010
	150	.5021	+ .0014
Estes D12	0	.7491	- .0019
	32	.7500	- .0010
	70	.7510	
	100	.7519	+ .0009
	125	.7525	+ .0015
	150	.7532	+ .0022
FSI Loadlifter	0	.8740	- .0022
	32	.8750	- .0012
	70	.8762	
	100	.8771	+ .0009
	125	.8780	+ .0018
	150	.8788	+ .0026

Nominal grain diameters are assumed to be at 0° C (32° F) for ease of calculation.

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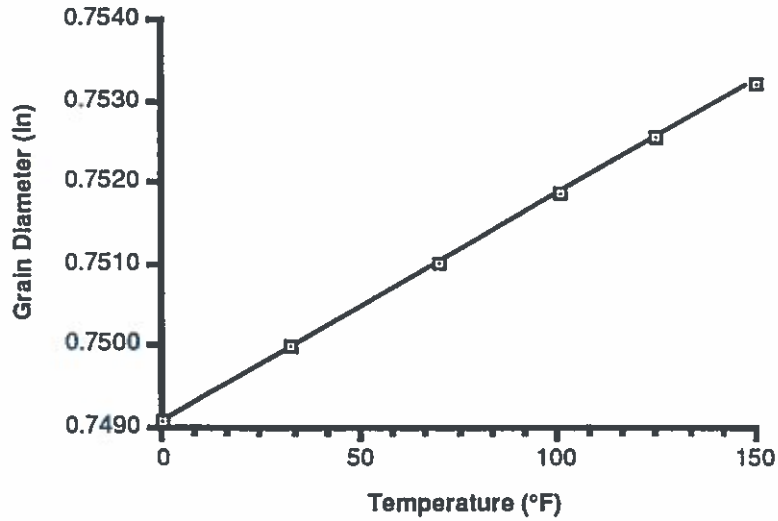

FIGURE 7 TEMPERATURE VS. GRAIN DIAMETER

Clearly, as the temperature rises, the larger diameter motors start to experience significant swelling of the grain at higher temperatures. Since we know that motors do not split wide open when exposed to these temperature, we must assume that the case expands by the same amount.

One might not worry about this phenomena if it were assumed that the case would return to its original diameter upon cooling. However, as we shall see later, this is not always the case in materials like the case.

Table 3 also indicates that if the grain gets cold enough, a gap may be created. The temperature that this may occur at appears to be too cold for all but the heartiest of rocketeers. Secondly, the internal equilibrium (as illustrated in Figure 2) load may cause the case to begin to contract around the grain and minimize the gap.

As a result, it appears that the source of most motor catastrophic failures occur as a result of hot temperature excursions. This fits in better with the typical scenario that a modeler encounters (i.e., a lot of rockets fly in hot weather, very few in cold), and agrees with Shector's results. Because of this, the analysis will concentrate on the hot temperature scenario that appears to be more common.

The generalized condition described above is primarily for a solid grain, typical of most Estes motors. If the motor is a core burner, such as the FSI "Loadlifter" series, additional problems may be encountered.

This is primarily due to the fact that the core configuration induces additional stresses on the grain. The hoop stress is the greatest at the center of the grain. At hot conditions, the core will bow outward (as illustrated in Figure

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8). The gap between the the case and the grain is likely to be even more pronounced than in solid grain configuration.

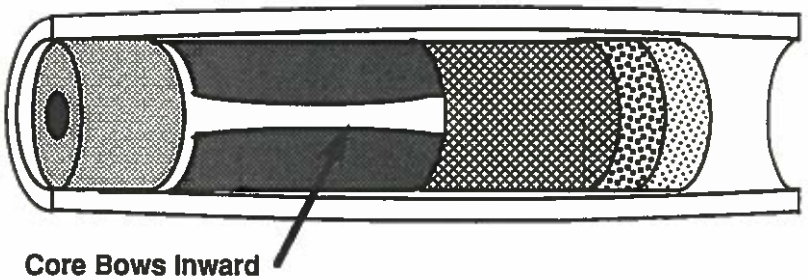

FIGURE 8
CORED MOTOR AT HIGH TEMPERATURE

Additionally, the forces of ignition pressurization work against this configuration. If a cored motor has a gap between the case and grain, the force of ignition pressurization may crack the grain, resulting in an increase in burning surface area and a cato.

Comparative failure rates for motors of roughly the same size (such as the FSI F7 and F100) seem to support the theory that cored black powder motors are more likely to fail.

STRUCTURAL CONSIDERATIONS

A convolute would paper motor casing is essentially a composite material— that is, a system that consists of an adhesive resin system and a reinforcing fiber. In this case, the fiber is the paper, and the resin is the glue that bonds the paper together.

Tensile testing of metals at normal temperature ranges generally show one basic type of stress-strain curve. Composites are generally more sensitive to time and temperature effects. It appears that the casing material for black powder motors has been assumed to reflect the basic characteristics of metal properties -- that is, there is little variation to stress-strain curve with time and temperature. Yet, it is quite clear that the manufacturing process takes advantage of the composite nature of the casing when the case walls are expanded slightly to compress the black powder grain. Because of this, it appears that techniques more common to the analysis of composites materials would be in order.

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Creep and Relaxation Phenomena

The phenomena of creep and relaxation is known and can be demonstrated in composite materials. Creep and relaxation can be illustrated by considering a test specimen that is loaded in tension.

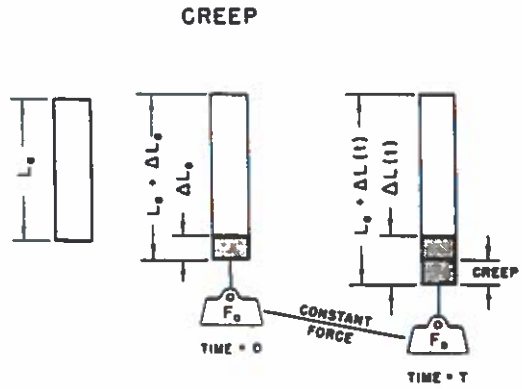

FIGURE 9 CREEP IN TENSION

In Figure 9, a force is applied to a specimen and an initial deformation is observed. With time, the test bar will permanently elongate. Creep is defined as non-recoverable deformation, with time, under a constant load. Consider a similar specimen caused by the same force, but in this case the specimen is confined to the initial deformation. As shown in Figure 10, the force decreases with time. Relaxation is defined as decrease of force, with time, required to produce a constant strain.

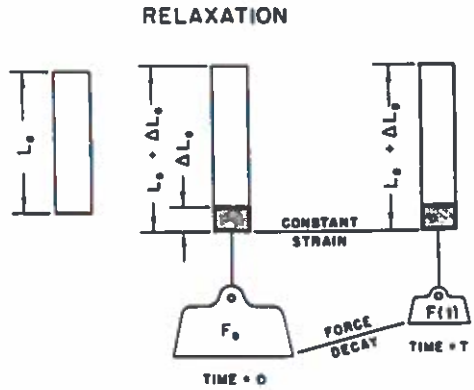

FIGURE 10 RELAXATION IN TENSION

Basic creep and relaxation behavior are measured by a simple uniaxial tension test. The data are usually given graphically. From the individual curves, the time-dependent moduli are calculated. The time-dependent creep modulus is defined as:

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(Equation 3) $$E_{t\ creep} = \frac{\text{Stress}}{\text{Strain at time (t)}} = \frac{F_0 / A_0}{\Delta L_t / L_0}$$

where
F_0 = Constant force, lb
A_0 = Original cross-sectional area, in.
L_0 = Original length, in.
ΔL = Increase in length at time (t) , in.

The time dependent relaxation modulus is similarly defined as:

(Equation 4) $$E_{t\ relax} = \frac{\text{Strain at time (t)}}{\text{Stress}} = \frac{F_t / A_0}{\Delta L_0 / L_0}$$

where
L_0 = Initial deformation, in.
F_t = Force at time (t), lb

Similar behavior can be shown for temperature effects.

The modulus accuracy limit is used as a checkpoint when making creep (deformation) and relaxation (force decay) calculation.

It has been shown experimentally that the creep modulus and relaxation modulus are similar in magnitude and for design purposes may be assumed to be the same. That is $E_{t\ creep} = E_{t\ relax}$. Therefore, only one time-dependent and temperature modulus (called the apparent modulus) is necessary.

Elastic design equations which were developed for metals can be applied to composites, such as a black powder rocket motor case. The deflection equations are expressed in terms of two material variables, the elastic (Young's) modulus and Poisson's ratio; while the stress equations are only dependent on load and geometry. These formulas can be converted to the appropriate time-dependent /temperature dependent equations by replacing the elastic modulus with the apparent time-dependent modulus and assuming Poisson's ratio to be a constant.

For practical purposes, Poisson's ratio is assumed to be constant with time. The other major assumption is that the stress distribution is initially linear and remains linear with time.

The radial displacement and the mean hoop stress of a casing under an induced load may be calculated using the following equations:

(Equation 6)

Radial displacement = $$Y = \frac{r}{E_t}\left(1 - \frac{\mu}{2}\right)\frac{P_i R}{t} \quad (7)$$

(Equation 7)

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Mean hoop stress = $S_b = \left(\frac{P_i R}{t}\right)$

Geometry of the case:

Mean radius of case = R = 0.50"
Wall thickness = t = 0.10"

Apparent modulus

$E_t \left(\frac{5 \text{ years}}{100 \quad F}\right)$ = 100,000 psi (assumed from similar composite type materials)

Assumed Load = 150 psi = P_j

Poisson's ratio = 0.40

$$Y = \frac{0.50}{10 \times 10^4} \left[(1-0.20) \frac{150 \times 0.50}{0.10}\right]$$

$$= 0.0029 \text{ in.}$$

$$S_h = \frac{0.50}{10 \times 10^4} = 750 \text{ psi}$$

$$\epsilon = \frac{S_h}{E_o} = \frac{750}{175.000} = 0.0043 \text{ in.in. or } 0.43\%$$

The calculation shows that the radius of the casing could increase by .0029" if exposed to this condition. The radial displacement is considered a realistic estimate since both the initial stress and strain did not exceed the modulus accuracy limit for this specific material (assumed to be 1400 psi, 0.85%).

Using the above equations, we can also demonstrate some useful properties:

A) The radial displacement is a function of the case radius. This means that small diameter cases, such as mini engines and standard size motors are less likely to experience significant displacement than larger diameter cases, such as the Estes D12 and FSI F100.

B) The increase in internal pressure is proportional to the amount that the grain diameter increases during expansion. Since the amount of increase in diameter is a function of the initial grain diameter, it follows that the smaller the grain

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diameter, the less likely case deformation and/or creep will take place.

C) Increasing the thickness of the case will minimize the displacement, if all other variables remain constant. However, there is a certain value above which increasing the thickness adds little margin. Figure 10 shows radial displacement as a function of wall thickness.

D) Older motors are more susceptible to creep. This is evident in the time dependent apparent modulus, which is lower than the elastic modulus

E) Obviously, a material with a higher apparent modulus or a higher Poisson's ratio will be more resistant to creep.

OBSERVATIONS

Generalized Failure Mode Scenario

As a result of these thermal and structural characterizations, the following generalized scenario can be developed:

1) If a motor is exposed to high temperatures, the grain will expand at a rate greater than the case. This induces an additional load on the case.

2) If the motor then returns to ambient temperatures, the grain contracts. The casing also contracts, but it may not contract all the way, due to the phenomena of creep.

3) The resulting gap between the propellant and casing may initiate a catastrophic failure.

This agrees closely with Shector's observed results.

Other Observations

Some other interesting observations can be made about this scenario:

1) A motor that has been exposed to warm or hot conditions, but has not returned to ambient, is likely to work, as no gap in the propellant/grain is present. This was also verified in Shector's tests.

2) A motor exposed to cold is unlikely to fail, unless the motor is exposed to a low enough temperature that the grain cracks or contracts away from the case wall.

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3) Cored motors are more likely to fail than end burners, due to the effect of ignition pressurization and increased hoop stresses in the core.

4) Motors with a small ratio of grain radius/casing thickness will be less likely to cato, due to the smaller amount of thermal expansion and a higher resistance to creep.

5) Any increase in temperature would tend to reduce the strength of the adhesive used in the casing. This would result in the apparent modulus value being lower than the elastic modulus.

Catastrophic Motor Failure Prevention

As a result of this analysis, there are two basic approaches that can be taken towards preventing catos in black powder motors. One involves what the modeler can do to prevent problems in motors available on the market today. The other is what current manufacturers can do to minimize the problem in future designs.

It is obvious from this analysis that the modeler should strive at all times to keep black powder motors at temperatures near ambient. Any significant temperature excursion can cause a motor failure, particularly in FSI motors and the Estes D12. If motors do get hot, it would be best to use them then, rather than allowing them to cool off. If motors are suspected of being hot cycled, re-heating the motors prior to flight might minimize catos (but this is only for the very brave). And, it can be seen that cold weather flying may induce catos, although this is not as likely to cause problems.

When black powder motors were designed, no one sat down and tried to determine the apparent modulus or Poisson's ratio for the case. What probably happened was that a case thickness and material was chosen from commercially available products. So, the design of a black powder model rocket motor is more likely the result of trial and error testing than of a carefully considered structural analysis.

If the designer is looking to improve the reliability of the black powder model rocket motor, the first approach might be to increase the case wall thickness and reduce the propellant mass. This is exactly what Estes did with the infamous D13, which was extremely cato prone. Even with these changes, the D12 (which is the reincarnated D13) still suffers from cato problems.

In some cases, reducing the propellant mass isn't practical. And, as Figure 10 demonstrates, increasing the thickness of the case wall will only help the situation to a point.

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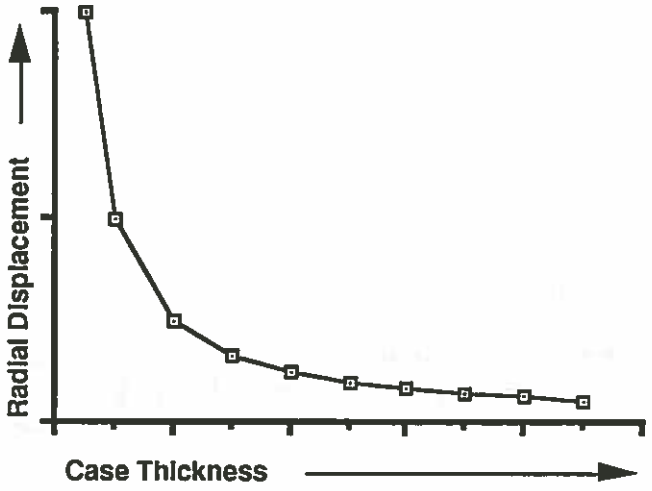

FIGURE 10 CASE WALL THICKNESS

That leaves the designer with two other choices -- find a material that has a coefficient of expansion that is closer to black powder's or find a casing material that is less resistant to creep. A quick review of common materials reveal that most non-metalic "structural" materials have low coefficients of thermal expansion, so the possibility of finding a material that would be suitable does not appear extremely likely. Rather, it would seem that the ideal course would be to attempt to find a casing material that is less susceptible to creep. With the advent of high strength plastics and elastomericised ablative resins (i.e., rubber compounds mixed with binding resins), it would seem that such a material might be available at a competitive commercial price and availability.

FURTHER WORK

Further effort in this area would include:

1) Finite element analysis of the black powder motor.

2) Thermal coefficient of expansion characterization of the black powder grain and case.

3) Experimental determination of the apparent modulus and Poission's ratio.

4) Characterization of alternate case materials for apparent modulus and Poisson's ratio.

5) Possible development of a black powder motor with an alternate case material.

6) Testing to see if "re-heating" temperature cycled motors reduces catos.

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CONCLUSIONS

The basic design flaw in most black powder motors is the fact that the effects of temperature and time have not been adequately accounted for in the motor case and motor grain design.

If it can be shown that the case and grain expand significantly when exposed to high temperatures. It is theorized that the casing suffers from creep, and does not totally relax when cooled. This creates a gap between the propellant and the casing, which can initiate a catastrophic failure. This scenario agrees closely with experimental observations.

It is suggested that black powder motor manufacturers investigate possible alternate casing materials in light of the new understanding. Until then, modelers are advised to keep their motors protected from temperature extremes, especially heat.

PROJECT COST

The cost of this project was less than $10 and was primarily used for reproduction and presentation materials.

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